

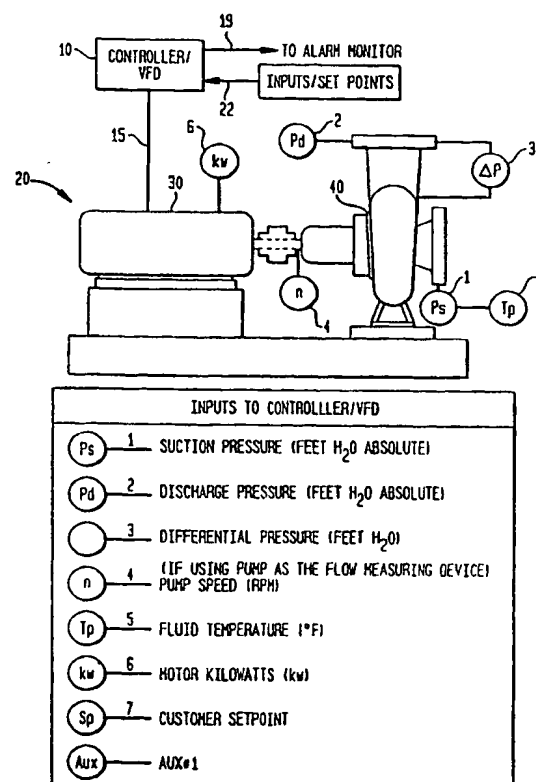


## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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<b>(21) International Application Number:</b> PCT/US99/28935 <b>(22) International Filing Date:</b> 7 December 1999 (07.12.99) <b>(30) Priority Data:</b> 09/275,498                      24 March 1999 (24.03.99)                      US <b>(71) Applicant:</b> ITT MANUFACTURING ENTERPRISES [US/US]; 1107 North Market Street, Wilmington, DE 07458 (US). <b>(72) Inventors:</b> SABINI, Eugene, P.; 6 Prentiss Drive, Skaneateles, NY 13152 (US). LORENC, Jerome, A.; 5 Courtney Drive, Seneca Falls, NY 13148 (US). HENYAN, Oakley; 3708 E. Genessee Street, Auburn, NY 13021 (US). <b>(74) Agent:</b> CARLETON, Dennis, M.; Buchanan Ingersoll P.C., 20th floor, One Oxford Centre, Pittsburgh, PA 15219 (US).		<b>(81) Designated States:</b> AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).  <b>Published</b> <i>With international search report.</i> <i>With amended claims.</i>

**(54) Title:** APPARATUS AND METHOD FOR CONTROLLING A PUMP SYSTEM**(57) Abstract**

A controller (10) for controlling operating parameters associated with fluid flow, speed or pressure for a centrifugal pump (40) for pumping fluid, wherein at least one sensor (1-6) is coupled to the pump (40) for generating a signal indicative of a sensed operating condition. The controller (10) comprises a storage device for storing data indicative of at least one operating condition and a processor in communication with the sensor and operative to perform an algorithm utilizing the at least one sensor signal and the stored data indicative of the at least one operating condition to generate a control signal, wherein the control signal is indicative of a correction factor to be applied to the pump.



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## **APPARATUS AND METHOD FOR CONTROLLING A PUMP SYSTEM**

### **FIELD OF THE INVENTION**

This invention relates generally to control systems, and more particularly to a controller for  
5 controlling flow, speed, pressure or performance of a pumping system.

### **BACKGROUND OF THE INVENTION**

A typical centrifugal pump of the prior art comprises an impeller, rotatably mounted in a  
stationary casing with the rotating impeller imparting pressure and kinetic energy to the fluid  
10 being pumped, and the stationary casing guiding the fluid to and from the impeller. In a typical  
centrifugal pump casing, which generally includes concentric, diffuser and volute type  
centrifugal casings, the rotation of the impeller imparts kinetic energy to the fluid and causes  
fluid flow, in a generally circular direction about the perimeter of the impeller, through the  
casing surrounding the impeller. At some point in the casing, the fluid flows from the perimeter  
15 of the impeller, passes a cut-water or the like through an area of the pump generally known as the  
discharge inlet area and through the discharge nozzle to the pump discharge.

The fluid flow can be affected by the design of the impeller, the design and size of the  
casing, the speed at which the impeller rotates, and design and size of the pump inlet and outlet,  
quality and finish of the components, presence of a casing volute and the like. In order to control  
20 fluid flow, variable frequency devices have been used to adjust the motor speed of the pump so  
as to regulate the flow within the pump system. It is to be noted that, as used herein, variable  
frequency drives are to include adjustable frequency drives (AFDs), Variable Speed Controllers  
(VSCs) or something similar, which operate to control electronic motor speed.

Pump speed and pressure represent important pumping system parameters, in addition to flow, which can cause the pump to operate at less than its most efficient level. Even more disadvantageously, less than optimal operating parameters may cause the pump and motor to work harder and thus wear out quicker, thereby shortening the pump's operational lifetime.

5 According, it is highly desirable to provide a computer-controlled variable frequency device (VFD) controller which utilizes computer algorithms and sensor inputs to control flow, speed, pressure and performance of a pumping system by monitoring motor, pump and system parameters and controlling pump output via speed variations. It is also advantageous to obtain a controller operative to identify and report pump or system anomalies to a technician, to facilitate  
10 investigation and correction of any abnormalities before any serious damage to the pumping unit occurs.

### **SUMMARY OF THE INVENTION**

A controller for controlling operating parameters associated with fluid flow, speed or  
15 pressure for a centrifugal pump for pumping fluid, wherein at least one sensor is coupled to the pump for generating a signal indicative of a sensed operating condition. The controller comprises a storage device for storing data indicative of at least one operating condition and a microprocessor in communication with the sensor and operative to perform an algorithm utilizing the at least one sensor signal and the stored data indicative of the at least one operating  
20 condition to generate a control signal, wherein the control signal is indicative of a correction factor to be applied to the pump.

There is also disclosed a method for automatically controlling operating parameters

associated with a centrifugal pump according to an algorithm for pumping fluid to a discharge outlet, comprising the steps of storing in memory data values corresponding to predetermined operating conditions, obtaining sensor measurements indicative of current operating conditions, utilizing the sensor measurements and the stored data values to determine calculated data values  
5 corresponding to the current pump operating conditions, and comparing the calculated data values with the stored data values and generating a control signal indicative of a correction factor to be applied to the pump when the calculated data values differ from the stored data values by a predetermined amount.

## 10 **BRIEF DESCRIPTION OF THE DRAWINGS**

Figure 1 is a block diagram of the pumping system and controller according to the present invention.

Figure 2 is a block diagram illustrating the microprocessor and storage associated with the controller for controlling the pumping system according to the present invention.

15 Figure 3A is a functional block diagram of the program controller modules operative for controlling the pumping system according to the present invention.

Figure 3B is an exemplary illustration of the pump data required for the program calculations of the controller.

20 Figure 3C is an illustration of the site specific data required for the calculations required for the controller.

Figure 3D is a more detailed block diagram of Figure 3A illustrating the major functional components associated with the controller according to the present invention.

Figure 4A is a block diagram illustrating the inputs and outputs for determining the capacity of the pumping system.

Figure 4B represents a flow chart depicting the steps involved in obtaining the flow calculation associated with the controller according to the present invention.

5        Figure 5A is a flow chart depicting the TDH logic module associated with the controller.

Figure 5B is a flow chart depicting the NPSH logic module associated with the controller.

Figure 6 is a flow chart depicting the capacity logic module associated with the controller.

10       Figure 7 is a flow chart depicting the pressure logic module associated with the controller.

Figure 8 is a flow chart depicting the low flow logic module associated with the controller.

Figure 9 is a flow chart depicting the wire-to-water efficiency logic flow module associated with the controller.

15       Figure 10 represents a data table of stored information comprising data values of water specific gravity v. temperature.

Figure 11 represents a data table of stored information comprising water vapor pressure v. pressure data.

20       Figure 12 represents a data table of stored information comprising pump pressure v. flow data at four different pump speeds.

Figure 13 represents a data table of stored information comprising pump performance data at four different pump speeds.

Figure 14 represents a data table of stored information comprising pump NPSHr data at four different pump speeds.

Figure 15 is a block diagram depicting the functioning of the variable speed control module associated with the controller.

5           Figure 16 is a detailed block diagram depicting the major functional software programs associated with the controller coupled to separate alarm monitor devices according to the present invention.

### **DETAILED DESCRIPTION OF THE INVENTION**

10           Referring now to Figure 1, there is shown a controller 10 coupled to a pumping system 20 comprising a motor 30 operative for powering centrifugal pump 40. Such a centrifugal pump is depicted in U.S. Patent 5,129,264 entitled CENTRIFUGAL PUMP WITH FLOW MEASUREMENT, issued July 14, 1992 and incorporated herein by reference. Note that when referring to the drawings, like reference numerals are used to indicate like parts. The controller, or variable/adjustable frequency device (VFD) 10, operates to control flow, speed or pressure of the pumping system by monitoring motor, pump and system parameters and controlling pump output via speed variation and identifying and reporting pump system problems. (Note that flow measurements may be obtained using conventional flow measuring devices such as ventures, orifice plates, mag meters and the like, as well as by the technique outlined in U.S. Patent No. 15 5,129,264.) Note further that the novel controller according to the present invention may be embedded within the VFD or may be externally connected between a VFD and the pumping system. More particularly, as will be described in more detail, the microprocessor containing the 20

executable software code for controlling the motor speed may reside physically within the VFD or external to the VFD. The latter implementation permits control for use with virtually any type of VFD devices.

As shown in Figure 1, sensors 1 - 6 are coupled to the pumping system 20 and are  
5 operative for sensing various operating conditions associated with the pump and inputting these values to controller 10 via communication line 22. Figure 2 shows a more detailed illustration of the controller 10 connected to the pump system 20. The controller comprises a processor 12 such as a microprocessor operative to perform software functions which utilize the sensor signals or sensor data obtained from each of the pump sensors to determine the pump operating  
10 conditions. The microprocessor 12 may be a large scale integrated (LSI) or VLSI integrated circuit controlled by software programs allowing operation of arithmetic calculations, logic and I/O operations. Other processors, including digital signal processors (DSPs) are also contemplated. Memory storage device or data base 14 such as a random access memory, (RAM) or other addressable memory is included within the controller for storing data values and tables  
15 associated with pump operating conditions and parameters. The microprocessor controller 12 receives the sensor signal data and processes the input data along with stored table data in memory 14. The microprocessor performs this processing by activating software programs which respond to the sensor inputs, as well as to pre-stored data parameters to perform a myriad of arithmetic calculations for comparison with threshold values. The software programs may be  
20 resident in microprocessor memory locations. Based on the results of those calculations and the comparison with threshold values, the software functions to generate an alarm signal indicative of an alarm condition associated with a particular operating parameter(s), and/or generates a



signal for input to the pumping system to alter the current motor speed to correct for an abnormal operating condition when the difference between the calculated and stored parameter values exceed a predetermined numeric value. The controller operates to generate a control signal to VFD logic within the VFD/controller 10 indicative of a request to reduce or increase motor speed in order to correct for detected abnormal condition. The VFD then generates a signal to the motor 30 corresponding to a change in voltage and/or frequency to cause the speed of the motor to change in an amount proportional to the controller generated control signal. The controller may also operate to generate a second output control signal 19 to an alarm monitor 23 indicative of a detected abnormality in order to alert a technician of the detected condition so as to allow him to investigate and/or adjust certain parameters associated with the operating conditions.

As shown in Figure 1, a plurality of sensor inputs from each of the sensors 1 - 6 are provided to the controller. These inputs include absolute pump suction pressure  $P_s$  (ref. numeral 1), absolute pump discharge pressure  $P_d$  (ref. numeral 2), differential pressure  $\Delta P$  (ref. numeral 3), pump speed  $n$  (ref. numeral 4), pumpage temperature  $T_p$  (ref. numeral 5) and motor power (ref. numeral 6). Note that pump suction pressure, pump discharge pressure, and the differential pressure are typically measured in feet  $H_2O$ , while the pump speed is in RPMs. Fluid temperature is preferably measured in degrees Fahrenheit, while the units associated with motor power are generally kilowatts (kw). Note further that the differential pressure for flow might be direct G.P.M. measured from a flow meter, while pump speed may be from either the controller or via direct measurement. In similar fashion, motor power may also be from the controller or via direct sensor measurement. An additional input 7 such as a customer adjustable parameter or set point may also be input into the controller 10 via a user interface (see Figure 3A) as the

parameter which operates to trigger a correction factor or an alarm in response to one of the sensed operating conditions. Additional auxiliary sensor inputs 8 may also be utilized by the controller such as additional pressure gauges for measuring barometric pressure. Note also that each of the sensors are conventional sensor elements such as transducers positioned on or within the pumping system in a well-known manner that act to translate each sensed operating condition into a corresponding electronic signal for input to the controller.

Figure 3A illustrates a block diagram of the controller software capabilities. As shown in Figure 3A, the controller includes a plurality of software programs 17 which execute algorithms and perform calculations associated with the monitoring of motor, pump and system parameters and for controlling, identifying and reporting on these parameters. The sensor input data from the pump is input to microprocessor 12 and received by a setup program 16 which performs initialization, timing control, scaling of the input data, and receipt and storage via memory 14 of parameter values. As also shown in Figure 3A the controller 10 includes a user interface portion 29 for receiving parameter data directly from a user, such as customer adjustable set points for trigger conditions, manual override for inputting a desired pump speed, or the site specific data (see Figure 3C) and/or pump data (see Figure 3B) required for the calculations performed by the software applications programs of module 17 and which are stored in memory 14. The setup program 16 initiates each of the subprograms in module 17, as will be explained in further detail below. The software associated with program 16 is operative to retrieve and display via the user interface 29 pump system parameters, inputted parameters as well as the sensor input and output conditions and calculated values resulting from the algorithmic execution in program module 17. The program also includes code which compares

the user entered setting information/parameters with threshold values stored in memory so as to avoid illegal operation settings. As one can ascertain, the software module 17 has program code to perform a number of calculations for determining the pump operating condition, and based on the calculated operating condition, and based on the calculated operating condition in

5 comparison with preset threshold values, the controller will send a control signal 15 to the pump motor 30 to either reduce or increase the motor speed. The control signal may have a variety of amplitude values and/or pulse widths indicative of the relative degree of increase or decrease of the motor speed relative to its present speed. Software programs 17 may also send a control

10 signal 19 to an alarm indicator 23 to indicate any failure or abnormality in the system which inhibits operation of the pump. The alarm control signal may also have varying amplitude values and/or pulse widths corresponding to the relative degree of severity of the alarm condition and/or the relative amount by which the sensed operating parameter exceeds the upper or lower

15 limits of the permissible operating conditions. Storage area 14 comprises storage media for storing site specific data required for software program execution and calculation and includes maximum pump speed, vapor pressure v. temperature, specific gravity v. temperature, capacity set point, and pressure set point and stability factor (cf). Such site specific data requirements for controller calculations are shown in Figure 3C. As shown in Figure 3B, pump data required for the controller calculations are stored in storage area 14, such as a database, and include pump

20 discharge diameter, pump suction diameter, suction gauge height to suction CL, net gauge height difference, minimum continuous capacity, minimum allowable capacity,  $TDH_{new}$  v. capacity at different speeds, and NPSHR v. capacity at different speeds.

Figure 3D shows a more detailed block diagram of the controller software capabilities of

program module 17 (Figure 3A) which generally comprise the following software modules:  
capacity/flow determination module 171, TDH performance logic module 173, NPSH logic 175,  
wire-to-water efficiency module 177, capacity flow control logic 179, pressure control logic  
181, low flow logic 183, and variable speed control module 185. The processing associated with  
5 each of these modules will be described below. In the preferred embodiment, each of these  
algorithmic processes are executed at a frequency of 10 times per second in order to sufficiently  
monitor and correct for any abnormalities. As can be seen from Figure 3D, each of the modules  
utilize in general, both the sensor data and stored parameter data (stored in memory 14) obtained  
from prior calculations to determine the pump operating conditions. The modules output control  
10 signals to activate either performance alarm 22 and/or to adjust the motor speed of motor 30.

Figure 4A shows a block diagram of the capacity determination module of the controller  
which receives as input the sensor inputs  $\Delta P$ ,  $T_p$ , and  $n$  in order to calculate the capacity of the  
pump system utilizing the technique disclosed in Patent 5, 129,264. Note also that the capacity  
 $Q$  can be obtained directly from a flow meter, as well as utilizing the above-mentioned  
15 technique.

Figure 4B represents a flow diagram for obtaining the flow calculation associated with  
flow determination software module 171. Referring to Figure 4B, pumpage temperature  $T_p$  and  
pump speed  $n$  sensor data is received and the specific gravity ( $S_pGR$ ) be selected from the  
parameter data in the data base comprising water specific gravity versus temperature, as shown in  
20 Figure 10. The software then operates to select from the parameter data illustrated in Figure 12  
of pump  $\Delta$  pressure versus flow at different speeds, the speed value in the data base having a  
value closest to the sensed pump speed from sensor 4. There exists in the data base 14 tabulated

values of flow in GPM as a function of  $\Delta$  ft. of pressure. The differential pressure ( $\Delta P$ ) input via sensor 3 is then used to determine and select the tabulated flow having a value of  $\Delta$  ft. pressure closest to the sensor input  $\Delta P$  value.

Referring to Figure 5A, there is depicted a flow diagram of the pump total dynamic head (TDH) logic portion 173 of the controller 10 which operates to determine the total dynamic head and pump performance. As shown in Figure 5A, data values associated with pumpage fluid specific gravity are stored in tables (or as equations) in memory 14, as well as the pump data (see Figure 3B). Such a table is illustrated in Figure 10. The TDH logic controller also processes table data associated with pumpage fluid vapor pressure (Figure 11) and  $\Delta$  pressure v. flow for up to six speeds as shown in Figure 12. The flow diagram of Figure 5A illustrates the following steps of determining the pump total dynamic head and comparing the calculated value with a threshold value. If the actual pump TDH at a given flow is below a preset value (e.g. 85-95% of the table value) then a control signal is output to activate a performance alarm. The TDH determination steps are as follows:

#### **Pump Total Dynamic Head (TDH) Determination**

- a. Determine the Net Velocity Coefficient of this pump.

$$C_v = 2.5939 \times 10^{-3} * (1/D_d^4 - 1/D_s^4)$$

Where  $D_s$  is pump discharge pipe diameter in inches.

$D_d$  is pump suction pipe diameter in inches.

$D_d$  and  $D_s$  parameters are input data.

- b. Determine Net Velocity Head of this pump

$$\Delta h_v = C_v * Q^2$$

Where  $C_v$  is Net Velocity Coefficient of this pump

$Q$  is pump flow in GPM from the flow calculation or directly from a Flow meter.

- c. Determine TDH

$$TDH = (P_d - P_s)/SG + \Delta Z + \Delta h_v$$

Where Pd is the pump discharge pressure (absolute) in ft.  
 Ps is the pump suction pressure (absolute) in ft.  
 ΔZ is net gage height difference input parameter data between Pd &  
 Ps gages in ft.  
 Ahv is the Net Velocity Head  
 and SP GR is pumpage specific gravity.

The pump performance comparison is then performed utilizing the actual pump speed, the flow value and the determined TDH value. The pump performance comparison method is identified below as follows:

### **Pump Performance Comparison**

- d. The actual pump speed in flow and calculated TDH are known.
- e. Select the pump performance data from the table of Fig. 13 having a speed closest to the actual pump speed.
- f. Correct the actual pump flow and TDH to table speed using the affinity laws:  
 $(Q1/Q2) = (N1/N2)$   
 $(TDH1/TDH2) = (N1/N2)^2$
- g. Using speed corrected pump flow and TDH values compare them to data values from the data base table in Fig. 13.
- h. If actual pump TDH at given flow is less than 85% to 95% (customer adjustable set parameter) of table value, then activate pump performance alarm.

Referring now to Figure 5B, a flow diagram of the net positive suction head (NPSH) logic controller portion 175 is illustrated. As shown in Figure 5B, inputs to the NPSH module comprise Q capacity, vapor pressure (Pv), specific gravity, pump suction pressure, pumpage temperature and fluid temperature. The net positive suction head available (NPSHa) is then determined as follows:

### **Net Positive Suction Head Available (NPSHa):**

- a. Actual pumpage temperature is known ( $T_p$ )
- b. Obtain the Vapor pressure (Pv) of pumpage from the stored parameter data in the data base as shown in Fig. 11.
- c. Determine Suction velocity head  
 $h_{vs} = (2.5939 * 10^{-3}) / D_s^4 * Q^2$  where

- Ds is pump suction pipe diameter input value in inches.
- d. Determine NPSHa  

$$\text{NPSHa} = (\text{Ps} + \text{Pv}) / \text{SG} + \Delta\text{Zs} + \text{hvs}$$
 where
- 5 Ps is pump suction pressure absolute in ft.  
 Pv is pumpage vapor pressure in ft.  
 SP GR is pumpage specific gravity determined from flow module 171.  
 $\Delta\text{Zs}$  is the difference in suction gage height to pump suction input data in ft.
- 10 hvs is suction velocity head in ft. determined from step c.

A comparison of the NPSHa versus NPSHr stored in the data base 14 (see Figure 14) is then made. If the NPSHa is less than the NPSHr, the program outputs a control signal to alarm and/or reduce the pump speed to prevent the pump from continuing to operate in a cavitating condition. The following steps depict the NPSHa v. NPSHr comparison steps.

#### **NPSHa vs NPSHr Comparison**

- a. Pump speed, flow and NPSHa are known.
- b. Retrieve the parameter data from the data base table from Figure 14 corresponding to the closest speed data.
- c. Correct the flow and NPSHa values using affinity laws to table speed.
- d. At the corrected flow, use data base table of Figure 14 to obtain NPSHr.
- e. If  $\text{NPSHr} > \text{NPSHa}$  for table speed then activate alarm via control signal; and
- f. output control signal to reduce speed by  $(\text{NPSHa}/\text{NPSHr})^2$  factor.

Note that as described in the NPSH logic portion of the controller, the calculated results are compared to the tabulated pump performance and NPSHr values, such that in the preferred embodiment, if performance is less than 95% (user selectable), then an alarm is activated. If the NPSHr of the pump is greater than the NPSHa of the system, alarm 23 is activated.

The controller 10 also includes a software program module 177 which performs a wire to water efficiency analysis. As shown in the flow diagram of Figure 9, the steps associated with this wire to water efficiency of the pumping system is as follows:

**Determine wire to water efficiency:**

- a. Calculate water horsepower generated  

$$\text{WHP} = (Q * \text{TDH} * \text{SG}) / 3960$$
 where Q is pump flow in GPM from module 171  
 TDH is pump head in ft. from module 173  
 SP GR is pumpage specific gravity
- b. Calculate electrical horsepower used.  

$$\text{EHP} = \text{KW} / .746$$
 where KW is kilowatt input in kilowatts (kw).
- c. Calculate wire to water efficiency of pumping system  

$$\mu_{\text{ww}} = \text{WHP} / \text{EHP}.$$

Figure 6 illustrates capacity logic portion 179 of the controller 10. As illustrated in Figure 6, the processing for flow control comprises setting the capacity (Q set), determining whether the capacity is within a desired range by comparing the actual capacity Qact to the Qset value, and adjusting the speed by a factor

$$N_{\text{new}} = (Q_{\text{act}} / Q_{\text{set}}) * n * \text{CF where}$$

CF is stability factor set by customer (typically .1 to 1.0). CF is used to prevent overcorrecting and instability in the control of the pump flow and speed as shown in Figure 6, the output control signal operates to either increase or decrease motor speed to the pump motor.

Figure 7 illustrates a process variable control for pressure determination module 181 associated with the controller 10. As shown in Figure 7, the steps associated with this variable control comprises:

- a. Comparing Pdact (actual Pd) to the Pdset. (Pump Discharge Pressure)
- b. Adjusting speed by a factor  $N_{\text{new}} = (\text{Pdact} / \text{Pdset})^{.5} * n * \text{CF where}$
- c. CF is a stability factor set by customer (typically .1 to 1.0)  
 CF is used to prevent overcorrecting and instability in the control of the pump



pressure and speed.

As shown in figure 7, the output control signal of module 181 operates to either increase or decrease the pump motor speed.

Figure 8 illustrates a flow diagram of the low flow logic module 183 portion of the controller 10 which compares the operating pump flow to the pump's calculated minimum continuous flow. If the actual flow rate is below the minimum continuous flow, an alarm is activated. The operating pump flow is also compared to the pump's calculated minimum allowable flow, such that if the actual flow rate is below the minimum allowable flow, the software program operates to provide a control signal to activate an alarm and/or reduce pump speed to prevent the pump from continuing to operate below the minimum allowable flow. The following steps depict each of the above-identified conditions.

**Below minimum continuous flow:**

- a. Input minimum continuous flow (mcf) of the pump at the maximum (max) speed in gpm into database memory.
- b. The mcf at any speed is  $(N1/N_{max}) * mcf_{max}$ .
- c. If the  $Q_{act}$  is  $< mcf$  for a given speed, generate alarm signal to notify customer that flow is below the minimum continuous flow level.

**Below minimum allowable flow:**

- a. Input allowable flow (af) of the pump at the maximum (max) speed in gpm into database.
- b. The af at any speed is  $(N1/N_{max}) * af_{max}$ .
- c. If the  $Q_{act}$  is  $< af$  for a given speed, output control signal to alarm customer that flow is below the minimum allowable flow level.
- d. If  $Q_{act}$  is  $< af$  output control signal to reduce speed of pump to a minimum (ie 1000 rpm) to eliminate damage to the pump.
- e. User interface resumes control once the cause of the below allowable flow condition has been eliminated.

The variable speed control module 185 operates as depicted in the flow diagram of Figure

15. As shown in Figure 15, the desired pump speed is selected and input to the module via user interface 29. The selected pump speed input to module 185 via a user is stored in the data base 14 and a control signal is output from the controller to set the desired speed of motor 30.

As one can ascertain, the controller operates to notify and correct pump operating parameters including pump flow, pump performance, pump pressure and speed in order to effectively control and maintain the pump in an efficient and active state.

It will be understood that the embodiments described herein are exemplary, and that a person skilled in the art may make many variations and modifications without departing from the spirit and scope of the invention. For example, while there has been shown a single pump performance alarm monitor, it is to be understood that each of the software application modules may provide a separate control signal which may be directed to a separate respective alarm monitor including an LED or a buzzer which would alert the technician to the precise overflow or overload condition. Such a set of alarm monitors respectively coupled to the software modules is illustrated in FIG. 16. The alarm monitors may be connected to a separate computing system or computer network which may operate to alert an individual at a location remote from the location of the pump. The application program code associated with the software modules 16 and 17 may be written in a variety of higher level languages such as basic, C, or other high level languages and operates in combination with conventional operating systems in a well known fashion so as to properly communicate with the pump sensors, pump motor, and any peripheral devices. Moreover, as previously discussed, the controller may be housed within a VFD for receiving pump sensor data and outputting control signals to adjust the pump motor speed, or may be external to a VFD and located within an interface module and

connected to the VFD, such that all input data is sent to the controller via the VFD and a control signal to adjust motor speed is output from the controller to the VFD for adjusting the speed of the electronic pump motor. All such modifications are intended to be included within the scope of the invention as defined in the appended claims.

## CLAIMS

What is claimed is:

1. A controller for controlling operating parameters associated with fluid flow, speed or pressure for a centrifugal pump for pumping fluid, wherein at least one sensor is coupled to said pump for generating a signal indicative of a sensed operating condition, said controller comprising:

a storage device for storing data indicative of an at least one operating condition; and

a processor in communication with said sensor and operative to perform an algorithm utilizing said at least one sensor signal and said stored data indicative of said at least one operating condition to generate a control signal;

wherein said control signal is indicative of a correction factor to be applied to said pump.

2. The controller according to claim 1, wherein said correction factor is an increase or reduction in pump motor speed.

3. The controller according to claim 1, wherein said control signal is output to an alarm monitor for indicating an alarm condition within said pump.

4. The controller according to claim 1, wherein said processor performing said algorithm generates a first control signal indicative of a speed correction factor to be applied to said pump to adjust motor speed, and a second control signal indicative of an alarm condition for output to an alarm monitor for alerting to said sensed operating condition.

5. The controller according to claim 1, wherein said storage device comprises a data base, and wherein said stored data comprises physical pump data and site specific data for input to said algorithm.

5 6. The controller according to claim 5, wherein said at least one sensor comprises a suction pressure sensor  $P_s$ , a discharge pressure sensor  $P_d$ , a differential pressure sensor  $\Delta P$ , and a pump speed sensor  $n$ , each said sensor generating a corresponding signal indicative of the sensed operating condition.

10 7. The controller according to claim 6, wherein said algorithm comprises:  
a) determining the fluid flow;  
b) determining pump total dynamic head (TDH);  
c) comparing said total dynamic head value with said stored data wherein said control signal is output to an alarm monitor indicating an alarm condition when said determined total  
15 dynamic head at said determined flow is less than a preset value associated with said stored data value.

8. The controller according to claim 7, wherein said algorithm further comprises:  
d) determining net positive suction head available (NPSHa) and  
20 e) comparing with a stored value in the data base corresponding to a threshold value NPSHr based on said pump speed and fluid flow,  
wherein said control signal is output to an alarm monitor and indicative of an alarm condition

when said NPSHr exceeds said NPSHa.

9. The controller according to claim 8, wherein a second control signal is output by said processor for reducing motor speed of said pump by a predetermined amount when NPSHr  
5 exceeds NPSHa.

10. The controller according to claim 9, wherein said algorithm further comprises:

f) calculating a minimum continuous pump flow and comparing with the determined fluid  
flow;

10 wherein a third control signal is output to said alarm monitor indicative of an alarm  
condition when the determined fluid flow is less than calculated minimum continuous  
flow.

11. The controller according to claim 10, wherein said algorithm further comprises:

15 g) calculating a minimum allowable pump flow and comparing with the determined fluid  
flow;

wherein a fourth control signal is output to said alarm monitor indicative of an alarm  
condition when the determined fluid flow is less than the calculated minimum allowable  
flow.

20 12. The controller according to claim 11, wherein a fifth control signal is output from said  
processor for reducing pump speed when said determined fluid flow is less than said minimum

allowable flow.

13. A method for automatically controlling operating parameters associated with a centrifugal pump according to an algorithm for pumping fluid to a discharge outlet, comprising:

5 storing in memory data values corresponding to predetermined operating conditions;

obtaining sensor measurements indicative of current operating conditions;

utilizing said sensor measurements and said stored data values to determine calculated data values corresponding to the current pump operating conditions;

10 comparing said calculated data values with said stored data values and generating a control signal indicative of a correction factor to be applied to said pump when said calculated data values differ from said stored data values by a predetermined amount.

14. The method according to claim 13, wherein said sensor measurements include sensor data associated with pump suction pressure (Pd), discharge pressure (Ps), differential pressure  
15 ( $\Delta P$ ), pump speed (n), and fluid temperature (Tp)

15. The method according to claim 14, wherein said calculated data values comprise fluid flow value, pump total dynamic head (TDH), and net positive suction head available (NPSHa).

20 16. The method according to claim 15, wherein said stored data values comprise pump data and site specific data for determining said calculated data values.

17. The method according to claim 16, wherein said pump data comprises pump discharge diameter, suction diameter, suction gage height to suction CL difference ( $\Delta z_s$ ), net gage height difference ( $\Delta Z$ ).

5 18. The method according to claim 17, wherein said pump data further includes minimum continuous capacity (MCFMAX), minimum allowable capacity (AFMAX), TDH as a function of capacity at a plurality of motor speeds, and NPSHr as a function of capacity at a plurality of motor speeds.

10 19. The method according to claim 17, wherein said site specific data includes maximum motor speed ( $n_{max}$ ), vapor pressure as a function of temperature ( $p_v$ ), specific gravity as a function of temperature (SPGR), capacity set point ( $Q_{set}$ ), pressure set point ( $P_{dset}$ ), and stability factor ( $cf$ ).

15 20. A method of controlling the flow, speed, pressure, or performance of a pumping system comprising the steps of:

storing predetermined data values associated with particular flow, speed, pressure or performance values;

measuring environmental parameter data associated with the pump;

20 associating subsets of said predetermined stored data values with the measured environmental parameters to obtain calculated data values corresponding to at least one of said flow, speed, performance, or pressure values; and



comparing said calculated data values with a corresponding threshold value and generating a control output signal in response thereto when the difference exceeds a preset value.

21. The method according to claim 20, wherein the control signal is indicative of an alarm  
5 condition.

22. The method according to claim 20, wherein the control signal is indicative of a correction factor to be applied to one of said measured environmental parameters.

10 23. The method according to claim 20, wherein said stored predetermined data values include vapor pressure as a function of temperature, specific gravity as a function of temperature, and pump performance as a function of motor speed.

15 24. The method according to claim 23, wherein said stored predetermined data values further include differential pressure and flow as a function of motor speed and net positive suction head as a function of motor speed.

25. The method according to claim 24, wherein said environmental parameters include pump suction pressure, pump discharge pressure, pump speed, and pump differential pressure.

20 26. The method according to claim 25, wherein said environmental parameter data further include pumpage temperature, motor power, and user set points.

27. The method according to claim 20, wherein the step of storing predetermined data values comprises the step of storing pumpage fluid specific gravity, fluid vapor pressure, differential pressure and flow as a function of motor speed, pump performance parameters as a function of motor speed, and NPSH parameters as a function of motor speed.

5

28. The method according to claim 27, wherein the steps of obtaining calculated data values and comparing said calculated data values with a threshold value further comprises:

determining a fluid flow;

calculating a total dynamic head (TDH) value associated with said pump using

10 said determined fluid flow;

selecting from said stored predetermined data values those data values having a speed closest to measured motor speed environmental parameter data;

correcting actual pump flow and said TDH values using said stored predetermined data values associated with pump speed to obtain corrected pump flow and TDH values;

15 comparing said corrected pump flow and TDH values to said threshold values;

and

generating a control signal to activate an alarm in response thereto when the difference is greater than said preset value.

20 29. The method according to claim 28, wherein the steps of obtaining calculated data values and comparing said calculated data values with a threshold value further comprises:

determining net Positive Suction Head Available data value (NPSHa);

comparing said NPSHa with predetermined data values corresponding to a stored value of NPSH; and

generating a second control signal to activate an alarm when the stored value of NPSH is greater than said NPSHa value.

5

30. The method according to claim 29, wherein the steps of obtaining calculated data values and comparing said calculated data values with a threshold value further comprises:

generating a third control signal to reduce motor speed by a predetermined amount when the stored value of NPSH is greater than said NPSHa value.

10

31. The method according to claim 29, wherein the steps of obtaining calculated data values and comparing said calculated data values with a threshold value further comprises:

calculating a minimum continuous pump flow and comparing with the determined fluid flow; and

15 generating a third control signal to activate an alarm when the determined fluid flow is less than the calculated minimum continuous flow.

32. The controller according to claim 30, wherein the steps of obtaining calculated data values and comparing said calculated data values with a threshold value further comprises:

20 calculating a minimum allowable pump flow and comparing with the determined fluid flow; and

generating a fourth control signal to activate an alarm when the determined fluid flow is

less than the calculated minimum allowable flow.

33. The controller according to claim 28, wherein the steps of obtaining calculated data values and comparing said calculated data values with a threshold value further comprises:

5 comparing the determined fluid flow  $Q$  with a threshold value  $Q_{set}$  corresponding to a user settable fluid flow; and

generating a control signal to adjust motor speed by a factor of  $(Q/Q_{set})^n \cdot CF$  where  $n$  is the measured motor speed environmental parameter data and  $CF$  represents a user settable value.

10

34. The controller according to claim 33, wherein the steps of obtaining calculated data values and comparing said calculated data values with a threshold value further comprises:

comparing the determined pump discharge pressure  $P_d$  with a threshold value  $P_{dset}$

15 corresponding to a predetermined stored discharge pressure data value; and

generating a control signal to adjust motor speed by a factor of  $(P_d/P_{dset})^{.5 \cdot n \cdot CF}$ .

**AMENDED CLAIMS**

[received by the International Bureau on 07 June 2000 (07.06.00);  
original claims 4, 14 and 22 cancelled; original claims 1, 13 and 20 amended; other claims  
unchanged (4 pages)]

1. A controller for controlling operating parameters associated with fluid flow, speed or pressure for a centrifugal pump for pumping fluid, wherein at least one sensor is coupled to said pump for generating a signal indicative of a sensed operating condition, said controller comprising:
  - a storage device for storing data indicative of an at least one operating condition; and
  - a processor in communication with said sensor and operative to perform an algorithm utilizing said at least one sensor signal and said stored data indicative of said at least one operating condition to generate a control signal;wherein said control signal is indicative of a correction factor to be applied to said pump and said processor performing said algorithm generates a first control signal indicative of a speed correction factor to be applied to said pump to adjust motor speed, and a second control signal indicative of an alarm condition for output to an alarm monitor for alerting to said sensed operating condition.
2. The controller according to claim 1, wherein said correction factor is an increase or reduction in pump motor speed.
3. The controller according to claim 1, wherein said control signal is output to an alarm monitor for indicating an alarm condition within said pump.

allowable flow.

13. A method for automatically controlling operating parameters associated with a centrifugal pump according to an algorithm for pumping fluid to a discharge outlet, comprising:

storing in memory data values corresponding to predetermined operating conditions;

obtaining sensor measurements indicative of current operating condition, said sensor measurements including sensor data associated with pump suction pressure (Pd), discharge pressure (Ps), differential pressure ( $\Delta P$ ), pump speed (n), and fluid temperature (Tp);

utilizing said sensor measurements and said stored data values to determine calculated data values corresponding to the current pump operating conditions;

comparing said calculated data values with said stored data values and generating a control signal indicative of a correction factor to be applied to said pump when said calculated data values differ from said stored data values by a predetermined amount.

15. The method according to claim 14, wherein said calculated data values comprises fluid flow value, pump total dynamic head (TDH), and net positive suction head available (NPSHa).

16. The method according to claim 15, wherein said stored data values comprise pump data and site specific data for determining said calculated data values.

17. The method according to claim 16, wherein said pump data comprises pump discharge diameter, suction diameter, suction gage height to suction CL difference ( $\Delta z_s$ ), net gage height difference ( $\Delta Z$ ).

18. The method according to claim 17, wherein said pump data further includes minimum continuous capacity (MCFMAX), minimum allowable capacity (AFMAX), TDH as a function of capacity at a plurality of motor speeds, and NPSHr as a function of capacity at a plurality of motor speeds.

19. The method according to claim 17, wherein said site specific data includes maximum motor speed ( $n_{max}$ ), vapor pressure as a function of temperature ( $p_v$ ), specific gravity as a function of temperature (SPGR), capacity set point ( $Q_{set}$ ), pressure set point ( $P_{dset}$ ), and stability factor ( $cf$ ).

20. A method of controlling the flow, speed, pressure, or performance of a pumping system comprising the steps of:

storing predetermined data values associated with particular flow, speed, pressure or performance values;

measuring environmental parameter data associated with the pump;

associating subsets of said predetermined stored data values with the measured environmental parameters to obtain calculated data values corresponding to at least one of said flow speed, performance, or pressure values; and

comparing said calculated data values with a corresponding threshold value and generating a control output signal in response thereto when the difference exceeds a preset

value, the control signal being indicative of a correction factor to be applied to one of said measured environmental parameters.

21. The method according to claim 20, wherein the control signal is indicative of an alarm condition.

23. The method according to claim 20, wherein said stored predetermined data values include vapor pressure as a function of temperature, specific gravity as a function of temperature, and pump performance as a function of motor speed.

24. The method according to claim 23, wherein said stored predetermined data values further include differential pressure and flow as a function of motor speed and net positive suction head as a function of motor speed.

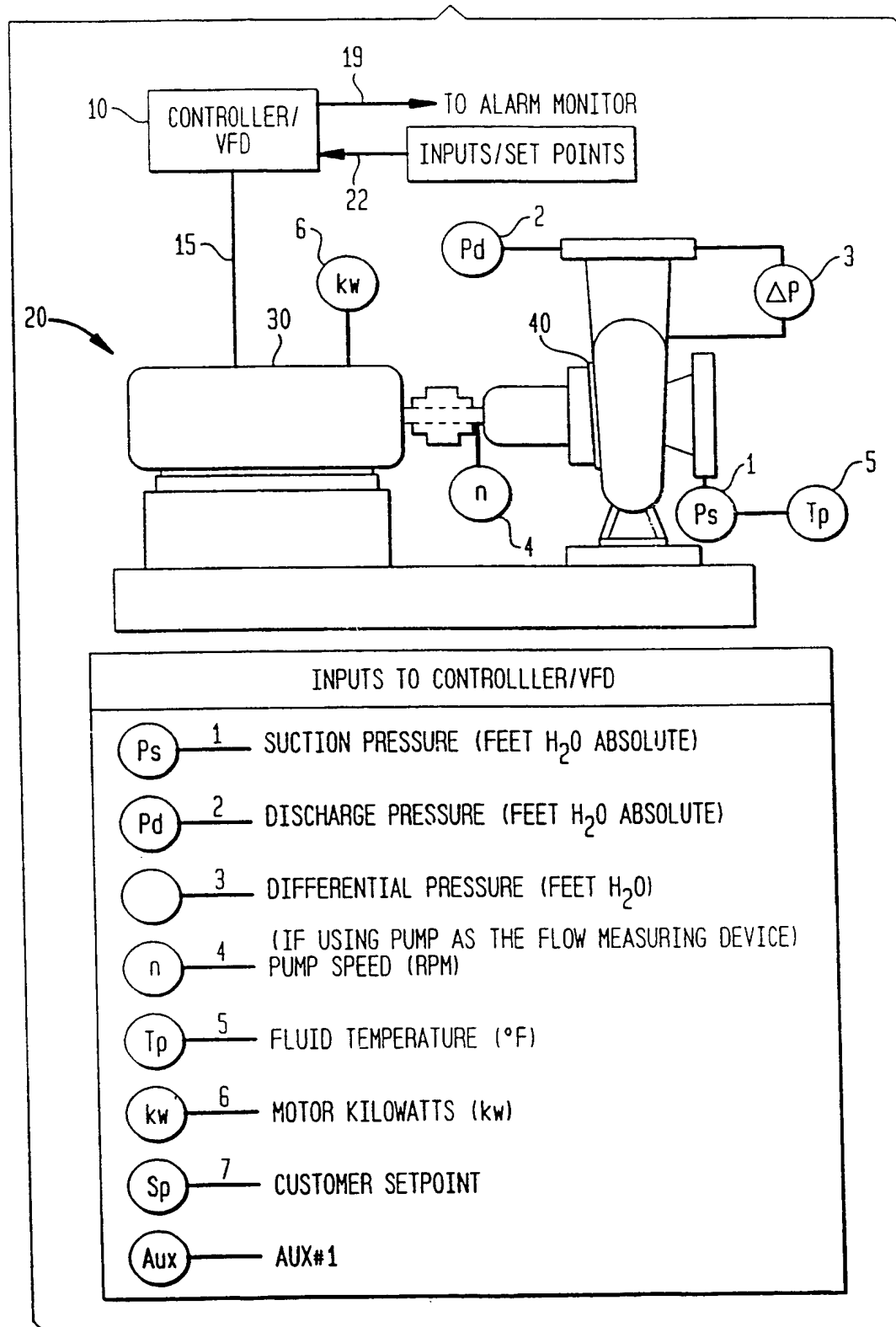
25. The method according to claim 24, wherein said environmental parameters include pump suction pressure, pump discharge pressure, pump speed, and pump differential pressure.

26. The method according to claim 25, wherein said environmental parameter data further include pumpage temperature, motor power, and user set points.



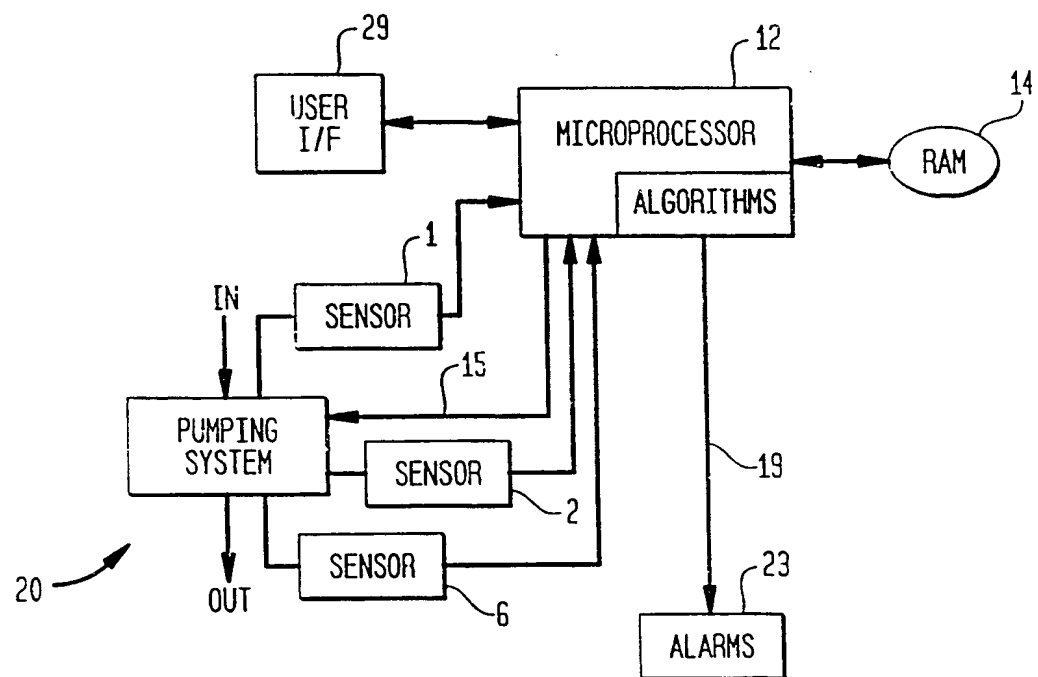
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FIG. 1



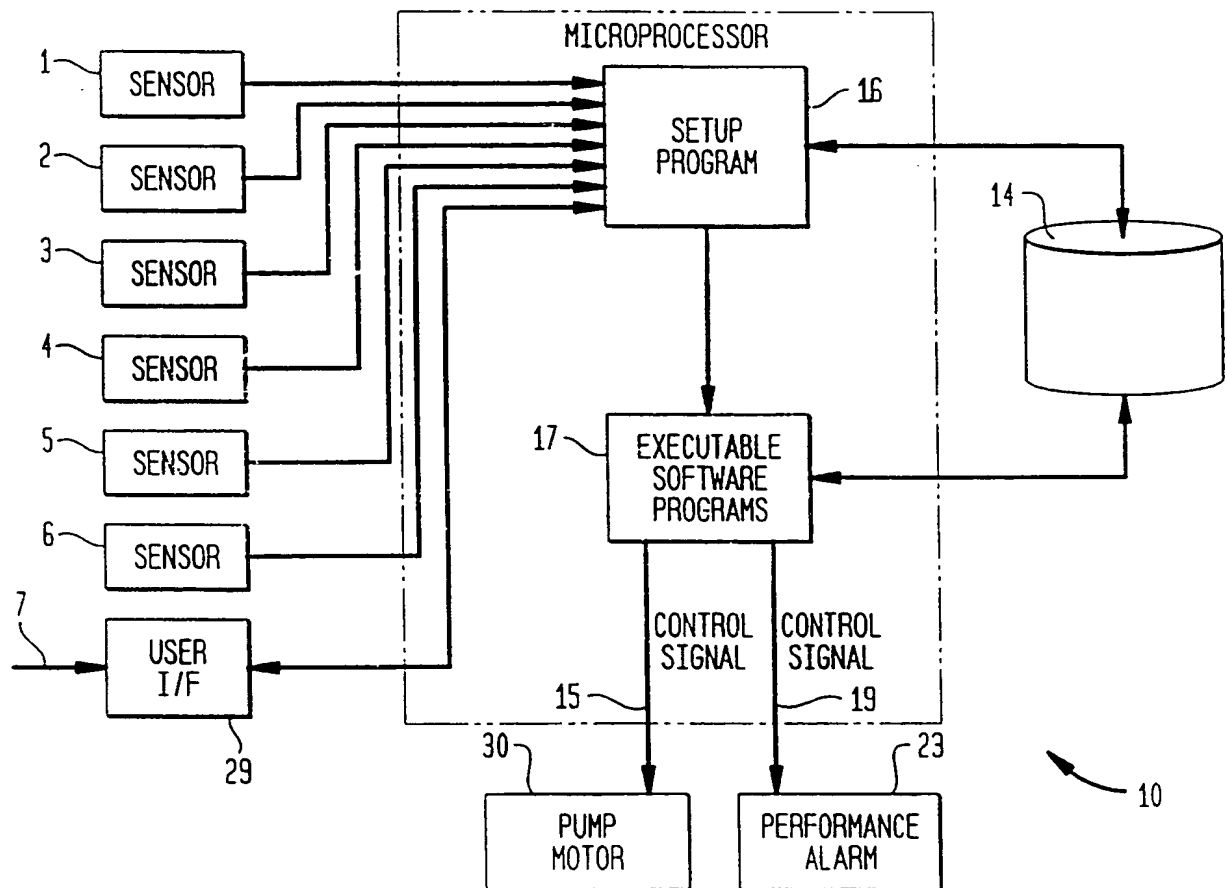
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FIG. 2



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FIG. 3A



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FIG. 3B

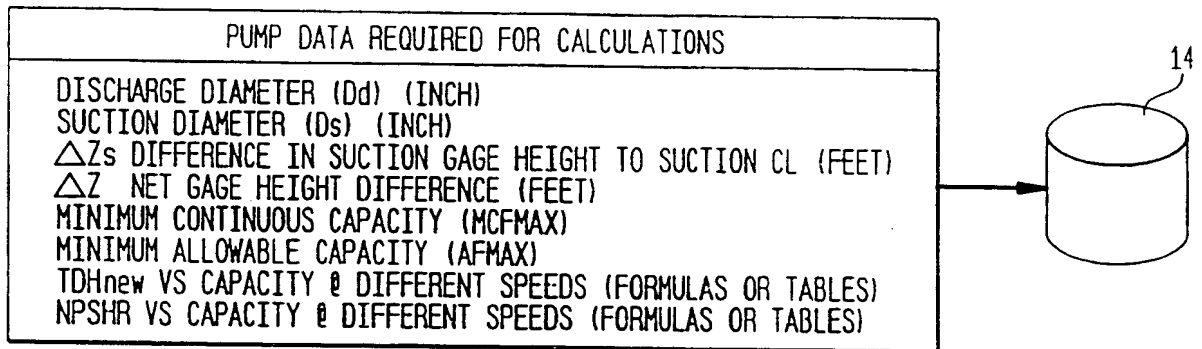
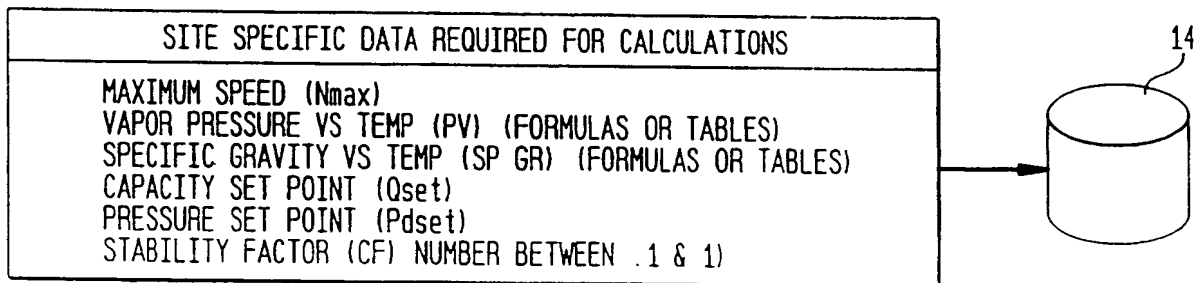


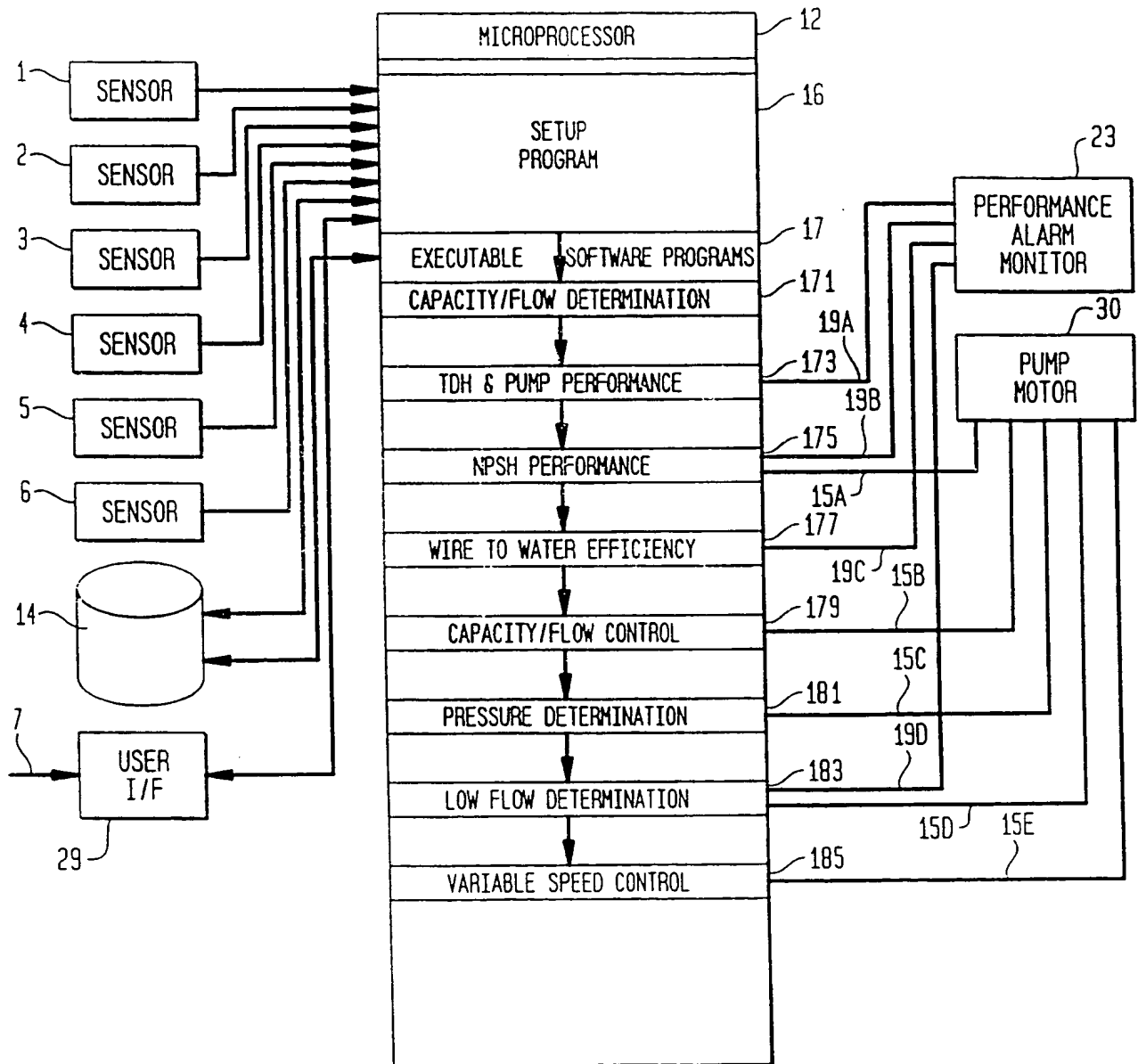
FIG. 3C



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FIG. 3D



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FIG. 4A

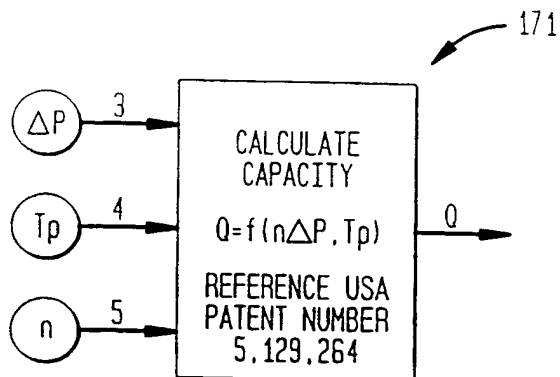
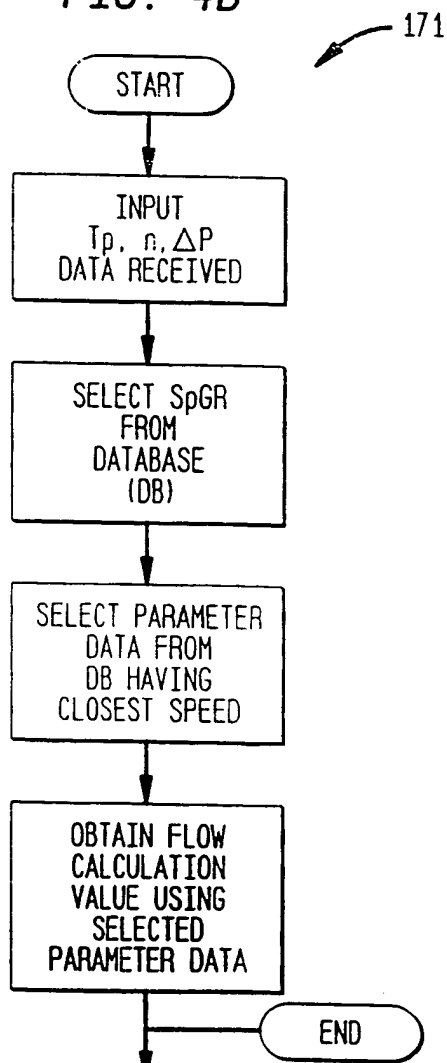
CAPACITY CALCULATION TECHNIQUE  
USING USA PATENT 5,129,264

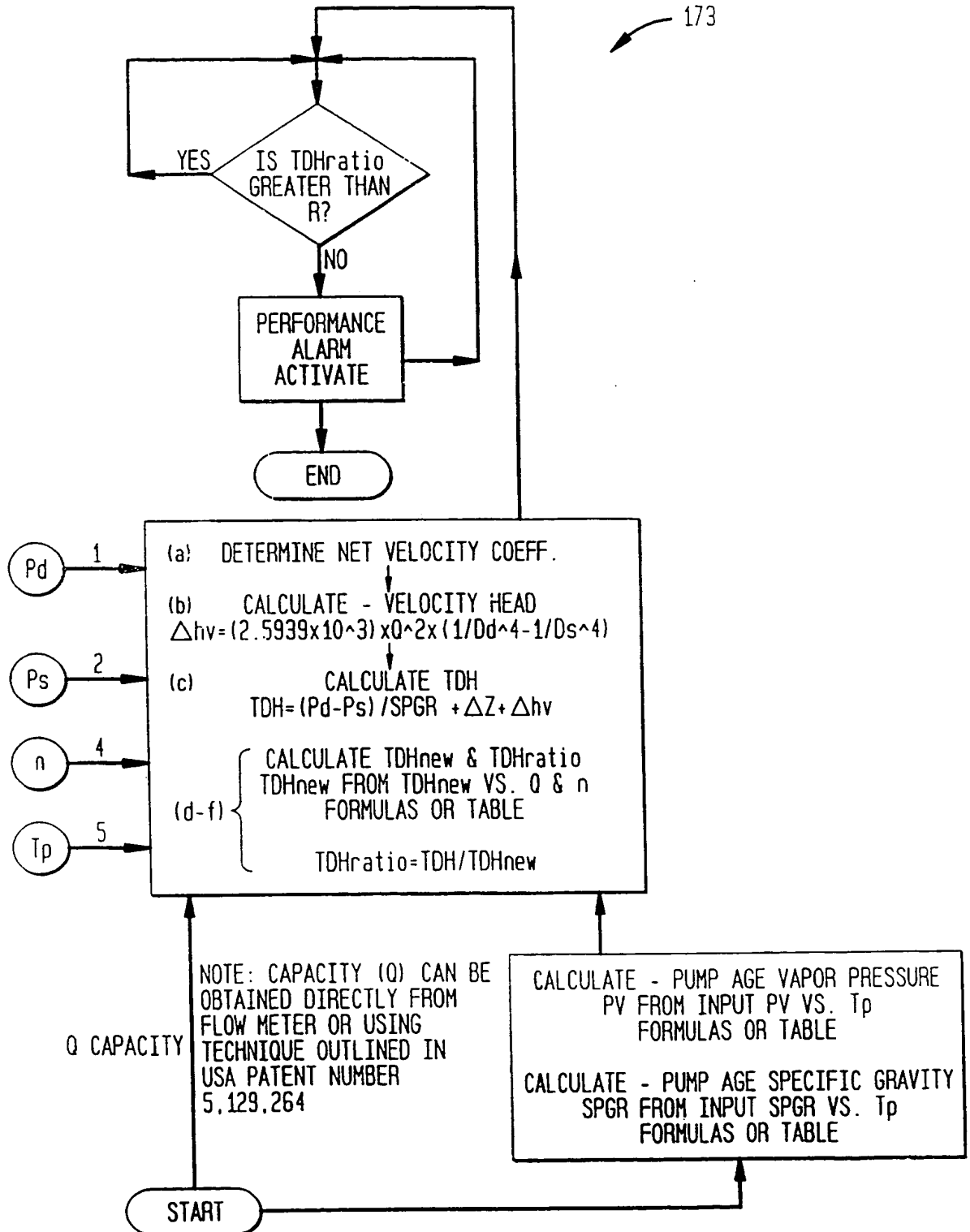
FIG. 4B



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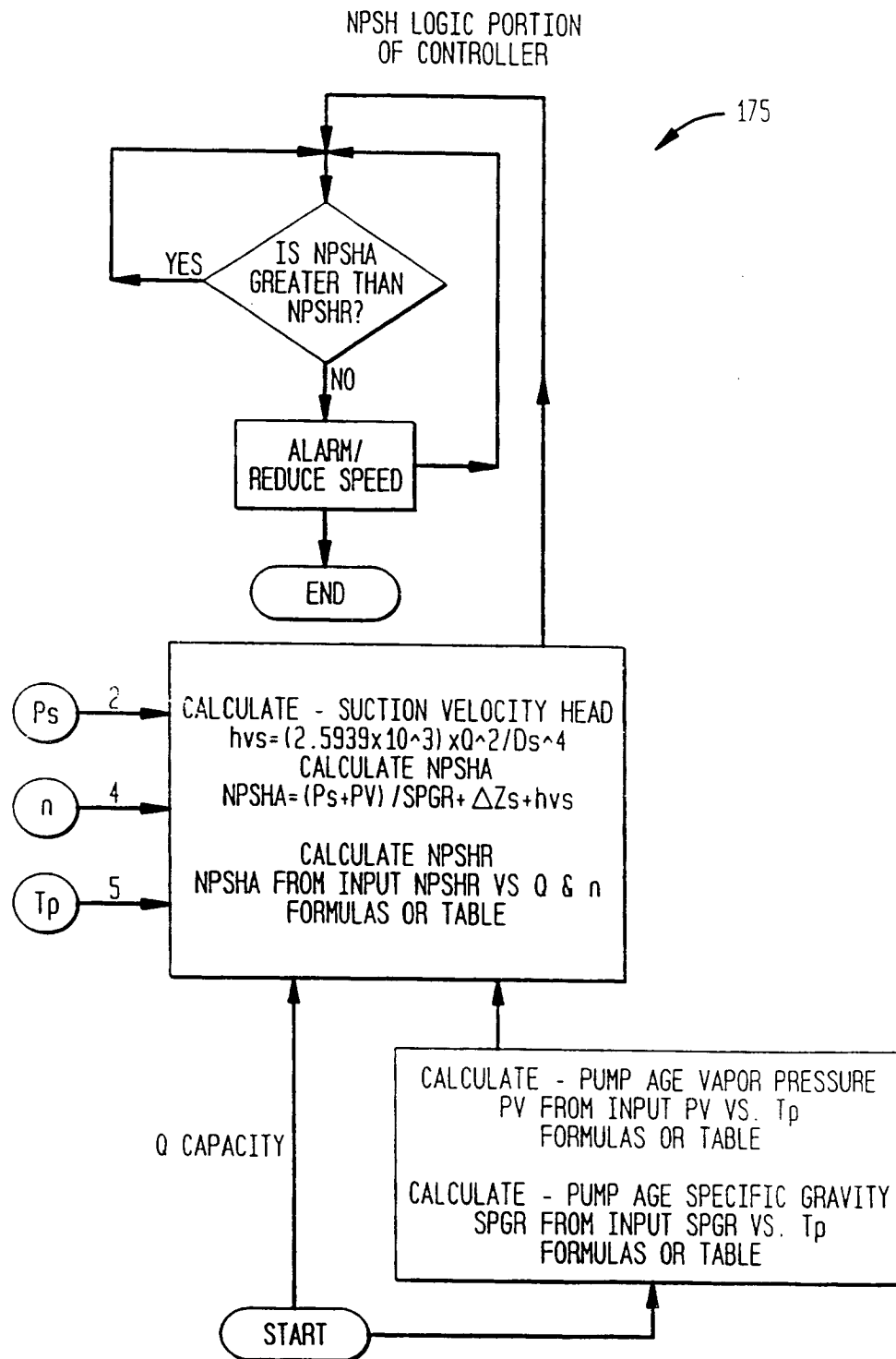
FIG. 5A

TDH LOGIC PORTION  
OF CONTROLLER

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FIG. 5B

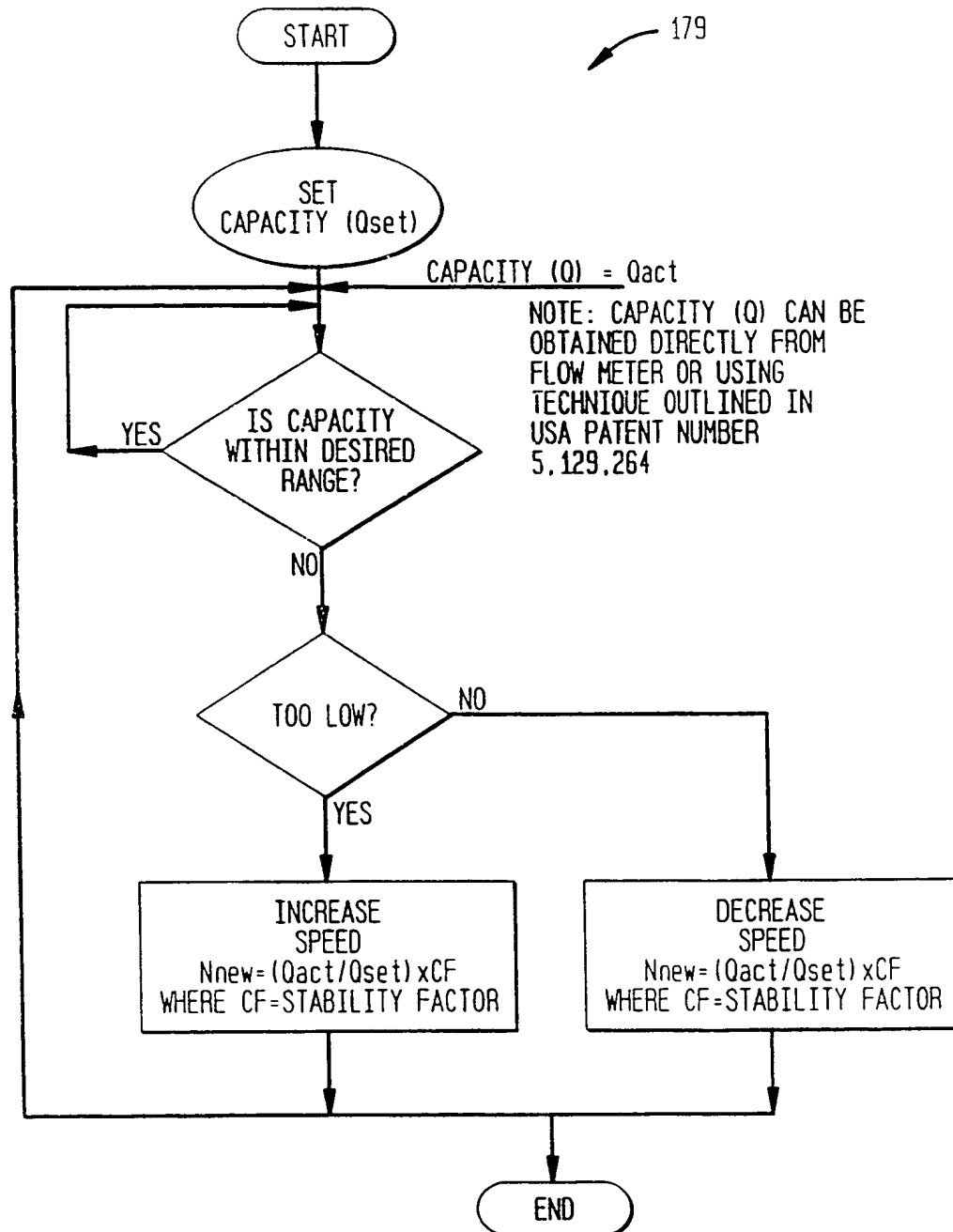


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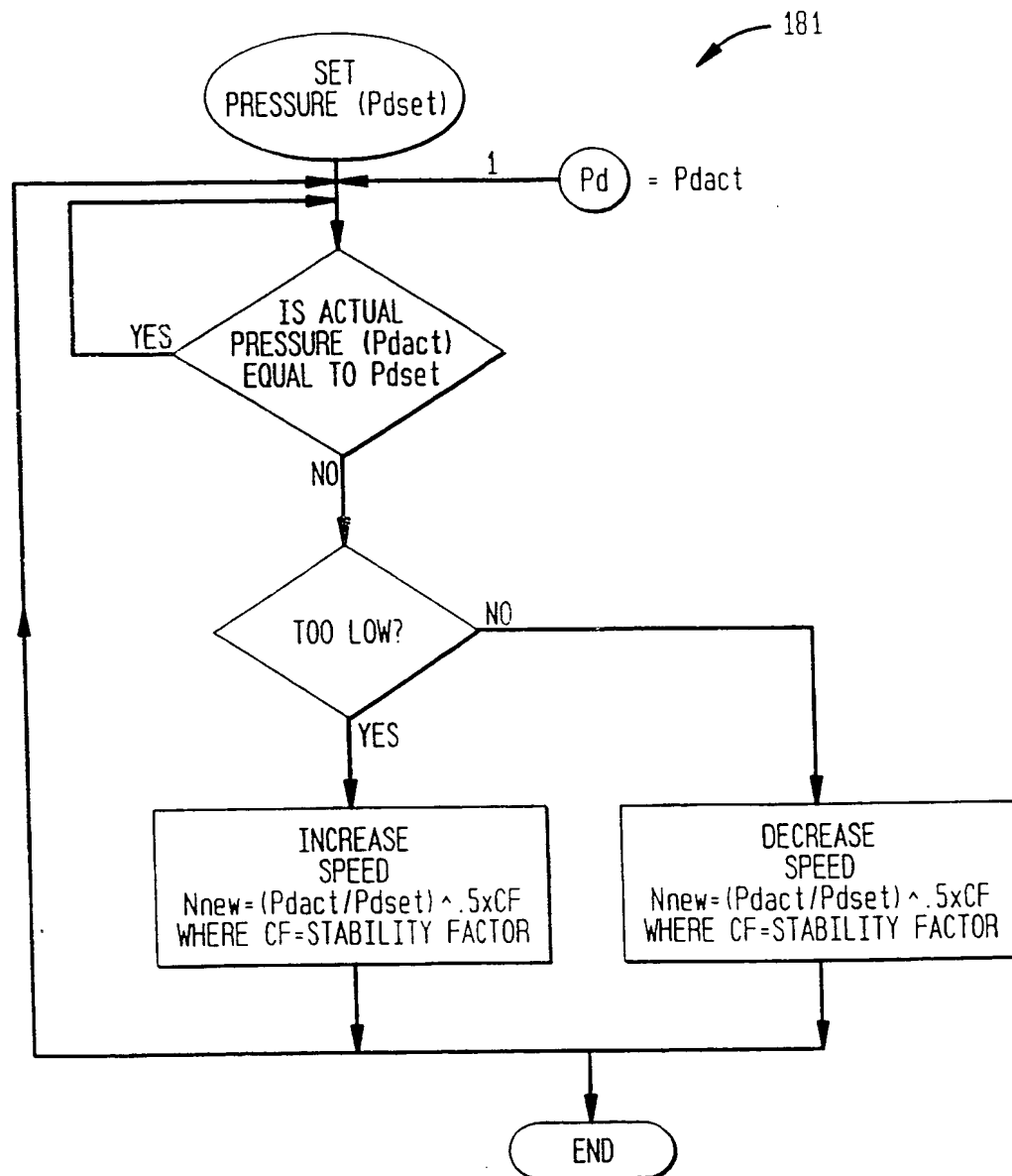
FIG. 6

CAPACITY LOGIC PORTION  
OF CONTROLLER

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FIG. 7

PRESSURE LOGIC PORTION  
OF CONTROLLER

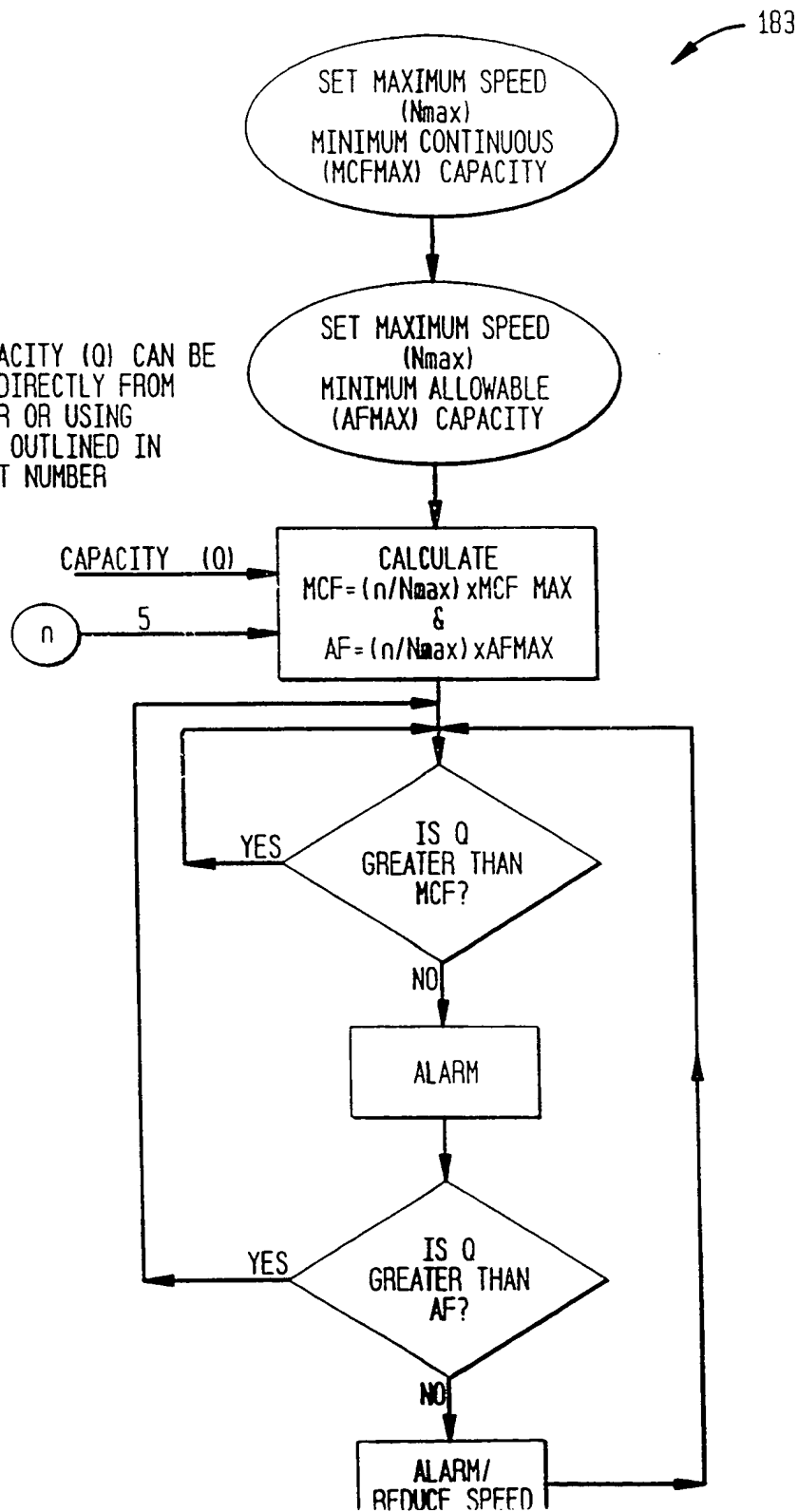
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FIG. 8

LOW FLOW LOGIC PORTION  
OF CONTROLLER

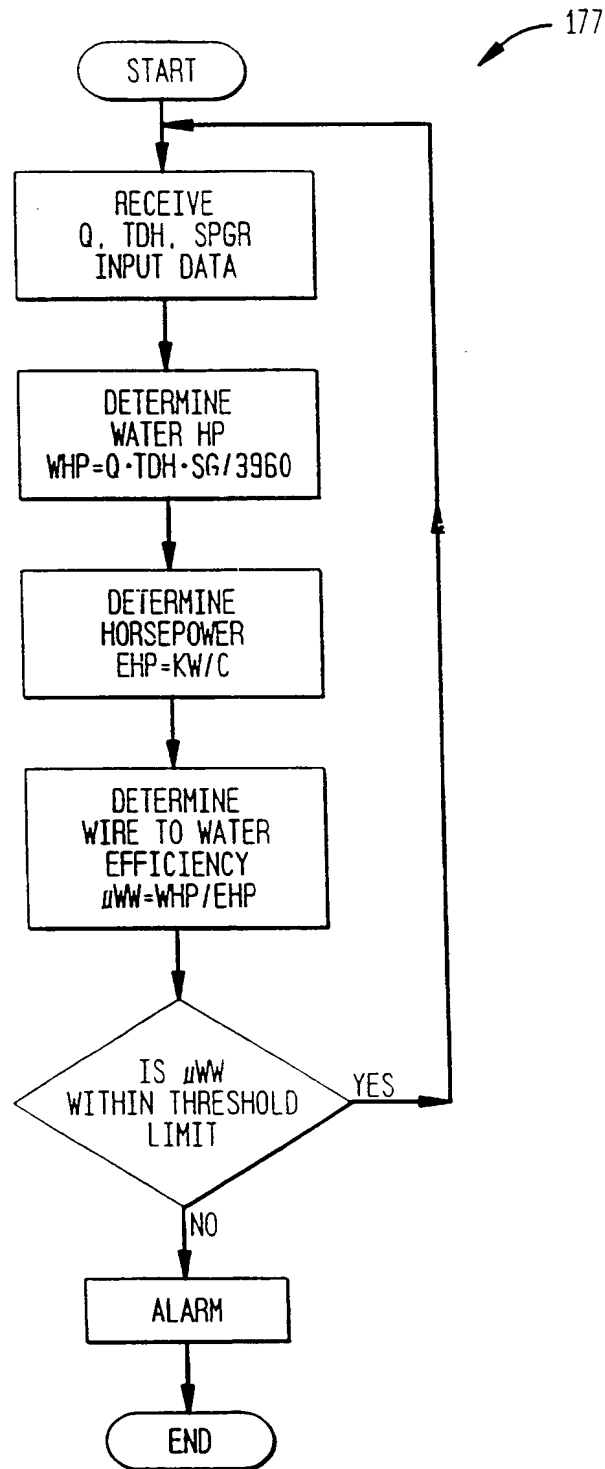
NOTE: CAPACITY (Q) CAN BE  
OBTAINED DIRECTLY FROM  
FLOW METER OR USING  
TECHNIQUE OUTLINED IN  
USA PATENT NUMBER  
5,129,264



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FIG. 9



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**FIG. 10**

## WATER SPECIFIC GRAVITY VS TEMPERATURE

TEMPERATURE	WATER SPECIFIC GRAVITY
32	1.0026
40	1.0024
50	1.0020
60	1.0012
70	1.0001
80	0.9988
90	0.9973
100	0.9954
110	0.9934
120	0.9911
130	0.9886
140	0.9858
150	0.9829
160	0.9797
170	0.9764
180	0.9729
190	0.9692
200	0.9653
210	0.9613

**FIG. 11**

## WATER VAPOR PRESSURE VS TEMPERATURE

TEMPERATURE	WATER VAPOR PRESSURE
32	0.22
40	0.27
50	0.39
60	0.58
70	0.84
80	1.18
90	1.63
100	2.21
110	2.95
120	3.91
130	5.13
140	6.66
150	8.58
160	10.95
170	13.85
180	17.37
190	21.61
200	26.67
210	32.64

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**FIG. 12**PUMP  $\Delta$  PRESSURE VS FLOW @ 4 SPEEDS

1780 RPM		3560 RPM		5340 RPM		6330 RPM	
PUMP FLOW	PUMP PRESSURE	PUMP FLOW	PUMP PRESSURE	PUMP FLOW	PUMP PRESSURE	PUMP FLOW	PUMP PRESSURE
0.0	0.0	0.0	0.5	0.0	0.4	0.0	0.7
9.8	0.2	9.4	0.7	10.0	0.5	9.6	0.3
20.2	0.3	19.9	1.1	20.6	1.1	19.4	1.1
30.0	0.9	30.1	1.5	30.5	1.6	30.2	2.0
40.3	1.8	40.4	1.9	40.9	1.9	39.5	2.1
51.7	2.8	50.2	2.8	59.4	3.4	59.9	3.0
55.0	3.6	70.4	5.3	80.1	6.6	79.4	6.4
60.3	4.3	90.0	8.9	99.6	10.2	99.1	10.1
64.9	5.1	99.4	10.9	119.4	15.1	140.0	21.0
69.6	6.0	110.2	13.3	141.6	22.0	161.4	28.0
74.3	7.1	118.8	16.3	160.0	28.8	178.1	35.8
		129.8	19.6	179.1	38.0	201.8	46.8
		149.0	33.1	200.6	47.8	217.2	57.5

**FIG. 13**

PUMP PERFORMANCE DATA @ 4 SPEEDS

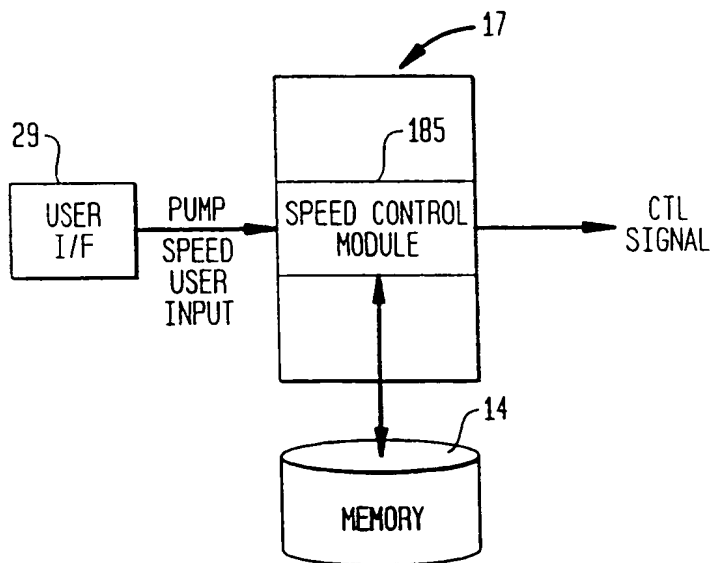
1780 RPM		3500 RPM		5340 RPM		6330 RPM	
PUMP FLOW	PUMP PRESSURE	PUMP FLOW	PUMP PRESSURE	PUMP FLOW	PUMP PRESSURE	PUMP FLOW	PUMP PRESSURE
0.0	41.7	0.0	159.0	0.0	370.1	0.0	520.1
5.0	41.5	10.0	159.0	15.3	370.1	18.1	520.1
10.0	41.1	20.0	158.0	30.5	367.8	36.2	516.8
15.0	41.0	30.0	157.0	45.8	365.5	54.3	513.5
20.0	40.4	40.0	155.0	61.0	360.8	72.3	507
25.0	39.7	50.0	153.0	76.3	356.2	90.4	500.5
30.0	38.9	60.0	151.0	91.5	351.5	108.5	493.9
35.0	37.9	70.0	147.0	106.8	342.2	126.6	480.8
40.0	37.0	80.0	144.0	122.1	335.2	144.7	471.0
45.0	35.8	90.0	138.0	137.3	321.2	162.8	451.4
50.0	34.3	100.0	132.0	152.6	307.3	180.9	431.8
55.0	33.1	110.0	128.0	167.8	298.0	198.9	418.7
60.0	31.2	120.0	122.0	183.1	284.0	217.0	399.1
65.5	29.4	130.0	114.0	198.3	265.4	235.1	372.9

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**FIG. 14**PUMP NPSH<sub>r</sub> DATA @ 4 SPEEDS

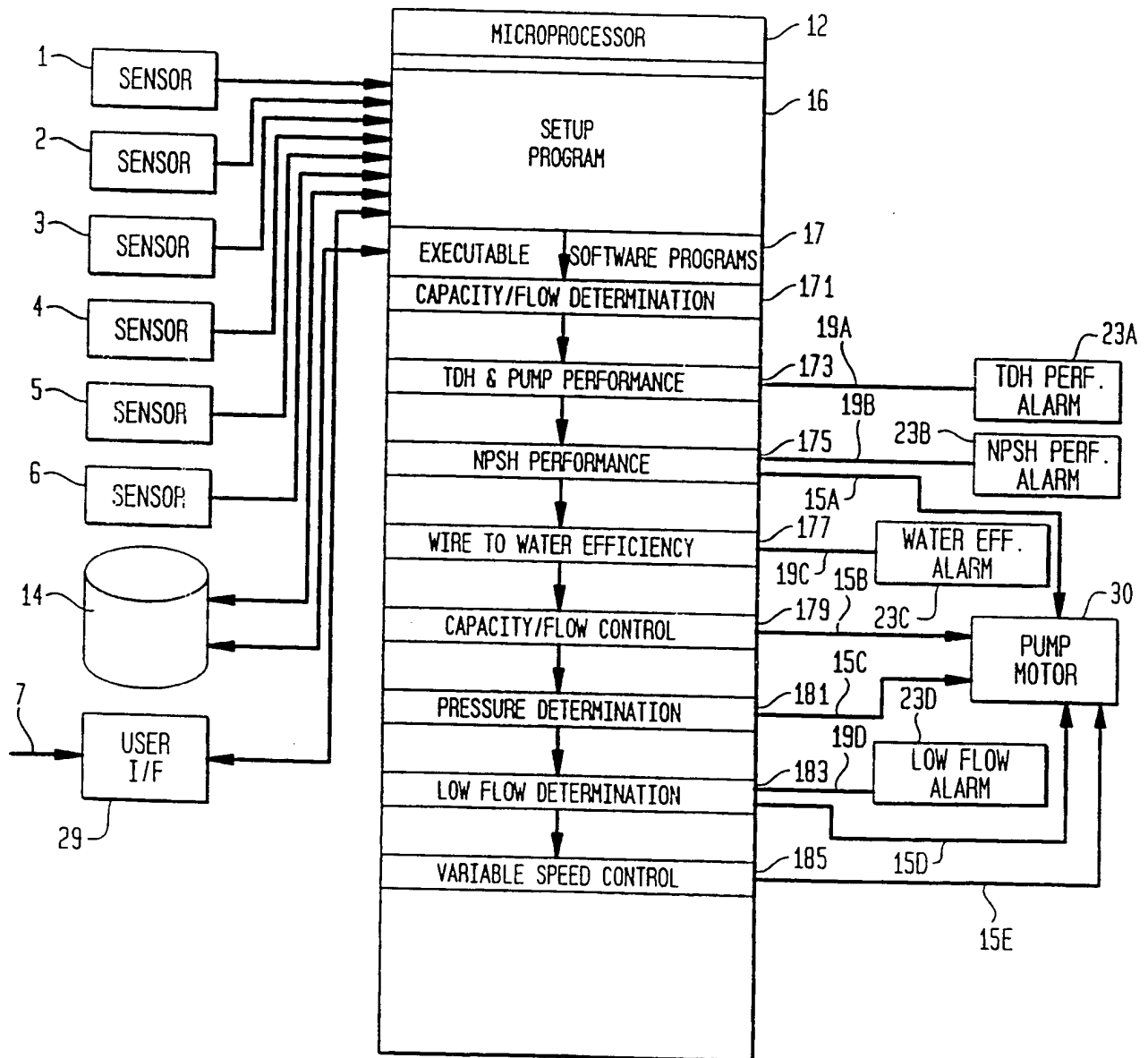
1780 RPM		3500 RPM		5340 RPM		6330 RPM	
PUMP FLOW	PUMP PRESSURE	PUMP FLOW	PUMP PRESSURE	PUMP FLOW	PUMP PRESSURE	PUMP FLOW	PUMP PRESSURE
5.0	2.0	10.0	2.0	15.3	4.7	18.1	6.5
10.0	2.0	20.0	2.0	30.5	4.7	36.2	6.5
15.0	2.0	30.0	2.0	45.8	4.7	54.3	6.5
20.0	2.0	40.0	2.3	61.0	5.4	72.3	7.5
25.0	2.0	50.0	2.7	76.3	6.3	90.4	8.8
30.0	2.0	60.0	3.4	91.5	7.9	108.4	11.1
35.0	2.0	70.0	4.1	106.8	9.5	126.6	13.4
40.0	2.0	80.0	5.1	122.1	11.9	144.4	16.7
45.0	2.0	90.0	5.8	137.3	13.5	162.8	19.0
50.0	2.0	100.0	7.1	152.6	16.5	180.9	23.2
55.0	2.0	110.0	7.9	167.8	18.4	198.9	25.8
60.0	2.5	120.0	9.0	183.1	21.0	217.0	29.4
65.5	3.0	130.0	10.8	198.3	25.1	235.1	35.3

**FIG. 15**

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FIG. 16



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## INTERNATIONAL SEARCH REPORT

Intern al Application No

PCT/US 99/28935

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 F04D15/00

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 7 F04D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 652 374 A (EBARA CORP) 10 May 1995 (1995-05-10) column 10, line 19 -column 11, line 21; claims 1,3,4; figures 1,9	1,2,5, 13,20
Y	----	3,21
Y	DE 32 36 815 A (METZGER KLAUS DIPL ING FH) 5 April 1984 (1984-04-05) page 3, line 6 - line 8	3,21
X	DE 42 43 118 A (CONTINENTAL AG) 23 June 1994 (1994-06-23) column 8, line 43 -column 11, line 12; figures 1-6	1,2,13, 20
A	CH 654 079 A (CERAC INST SA) 31 January 1986 (1986-01-31) the whole document	8,15,27, 29,30
	----- -/--	



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

## \* Special categories of cited documents :

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- \*L\* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- \*O\* document referring to an oral disclosure, use, exhibition or other means
- \*P\* document published prior to the international filing date but later than the priority date claimed

\*T\* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

\*X\* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

\*Y\* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

\*&\* document member of the same patent family

Date of the actual completion of the international search

17 April 2000

Date of mailing of the international search report

26/04/2000

Name and mailing address of the ISA

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Fax: (+31-70) 340-3016

Authorized officer

Teerling, J

## INTERNATIONAL SEARCH REPORT

Intern al Application No

PCT/US 99/28935

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 007, no. 102 (M-211), 30 April 1983 (1983-04-30) & JP 58 023294 A (EBARA SEISAKUSHO KK), 10 February 1983 (1983-02-10) abstract -----	1,2,13, 14,20
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